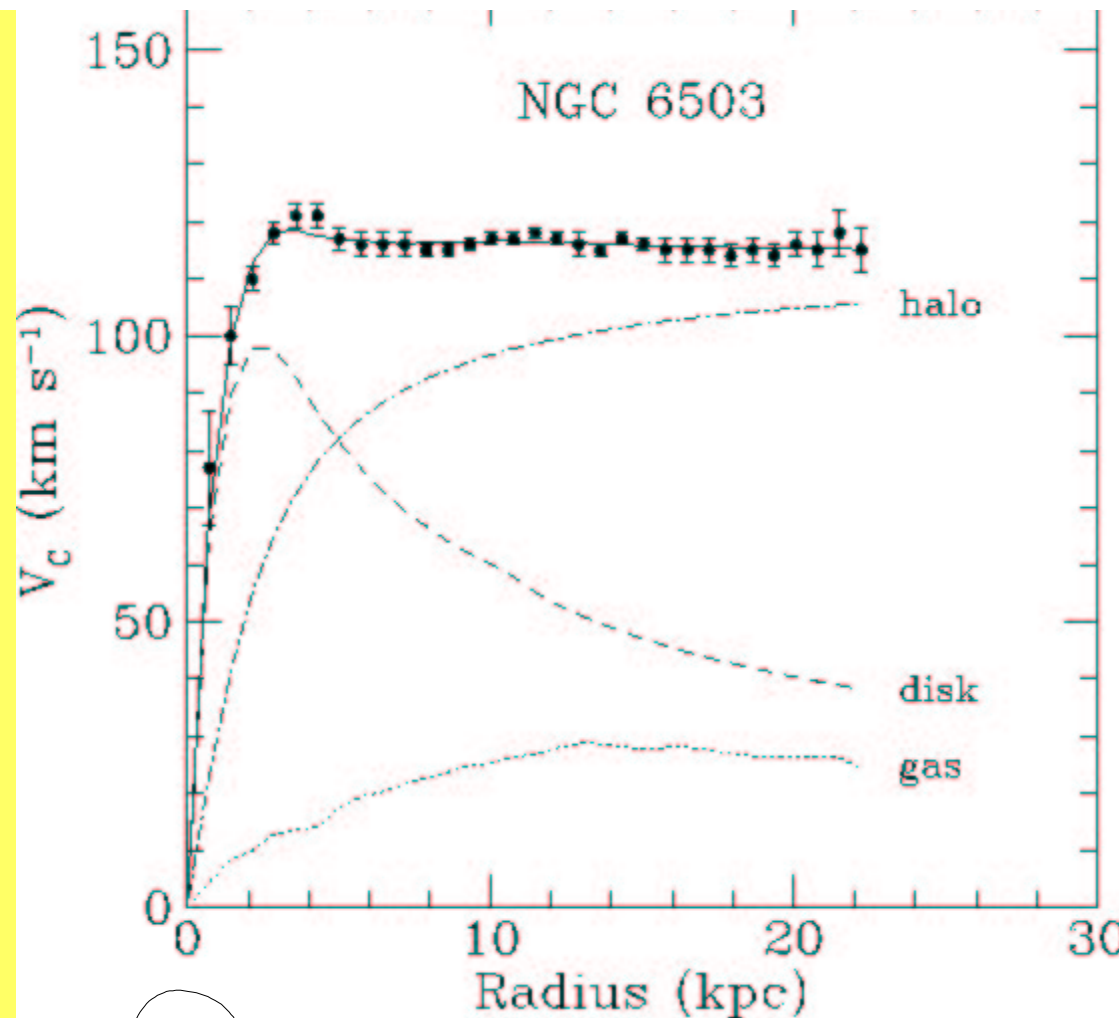


Do We Need Self–interacting dark matter?

Cosmo–02,
September 21, 2002
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(Caltech)

- I. Nonbaryonic dark matter
- II. Problems with collisionless dark matter
- III. Self–interacting dark matter (SIDM)
- IV. Astrophysical constraints



density

Core radius

$$\rho(r) = \rho_0 \frac{r_0^2 + a^2}{r^2 + a^2}$$

spherical halo:

$$\rho_0 = 0.3 - 0.6 \text{ GeV/cm}^3$$

If halo flattened,

$$\rho_0 \uparrow$$

velocity
distribution

~ Maxwell-
Boltzmann

With $\langle v^2 \rangle^{1/2} \sim 270 \text{ km/sec}$

Earth

$$r_0 = 8 \text{ kpc}$$

The standard smooth halo model

This stuff is not baryons

- H, D, He, Li abundances + BBN: $\Omega_b \approx 0.05$
- Peaks in CMB: $\Omega_b \approx 0.05$
- On the other hand, $\Omega_m \approx 0.3$ from dynamics, CMB, structure formation, classical tests....
- $\Omega_m \gg \Omega_b$ in clusters

Good news: cosmologists don't need to "invent" new particle:

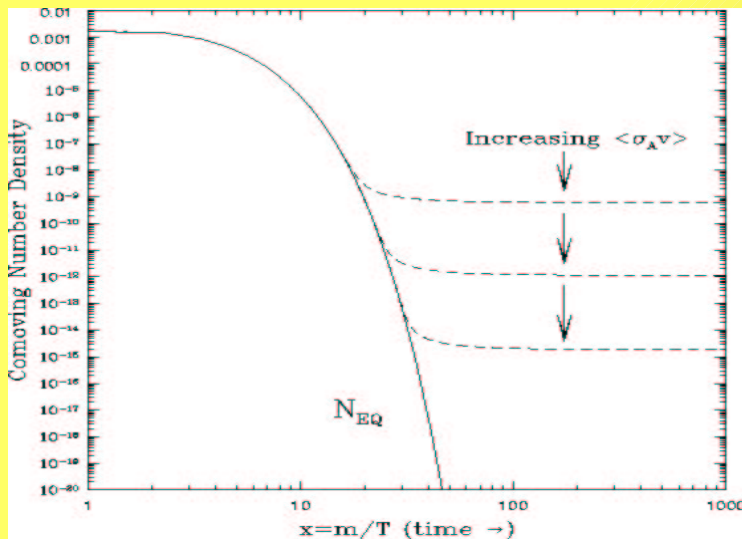
- Weakly Interacting Massive Particles (WIMPS). e.g., neutralinos

- Axions

$$m_a \sim 10^{-(3-6)} \text{ eV}$$

arises in Peccei–Quinn solution to strong–CP problem

(e.g., Raffelt 1990; Turner 1990)



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{ cm}^3 / \text{sec}}{\langle \sigma v \rangle} \quad (\text{e.g., Jungman, MK, Griest 1996})$$

WIMPs

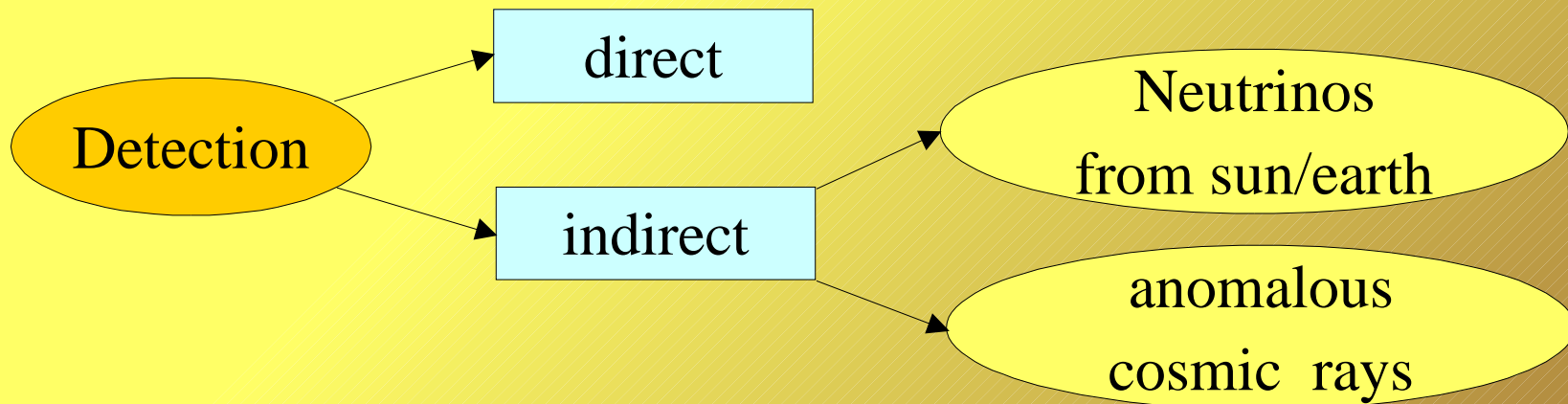
The relic density of a massive particle is about:

$$\Omega h^2 \approx \frac{3 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle v \sigma \rangle}$$

$\langle v \sigma \rangle$ Of **Weak Interaction** strength

the particle has to be coupled to SM particles

There is chance for detection:



WIMP candidate motivated by SUSY:

Lightest Neutralino, LSP in MSSM

Typical WIMP–WIMP elastic scattering cross section $\sim 10^{-40} \text{ cm}^2$ and mass 10–1000 GeV; for halo density $\sim \text{GeV}/\text{cm}^3$ and velocity $\sim 300 \text{ km/sec}$, mean–free time for WIMP scattering is at least $10^{13}/H_0$; thus, WIMPs act as collision–*free* dark matter.

Axion–axion cross section far smaller, so also collisionless.

Problem 1: Halo cusps

N-body simulations show "cusp", $\rho \sim 1/r$,
for small r for collisionless halos (Navarro,
Frenk, White 1996; Moore et al. 1997);
however, rotation curves for (at least some,
maybe most) galaxies show dark-matter cores.

Problem 2: Halo substructure

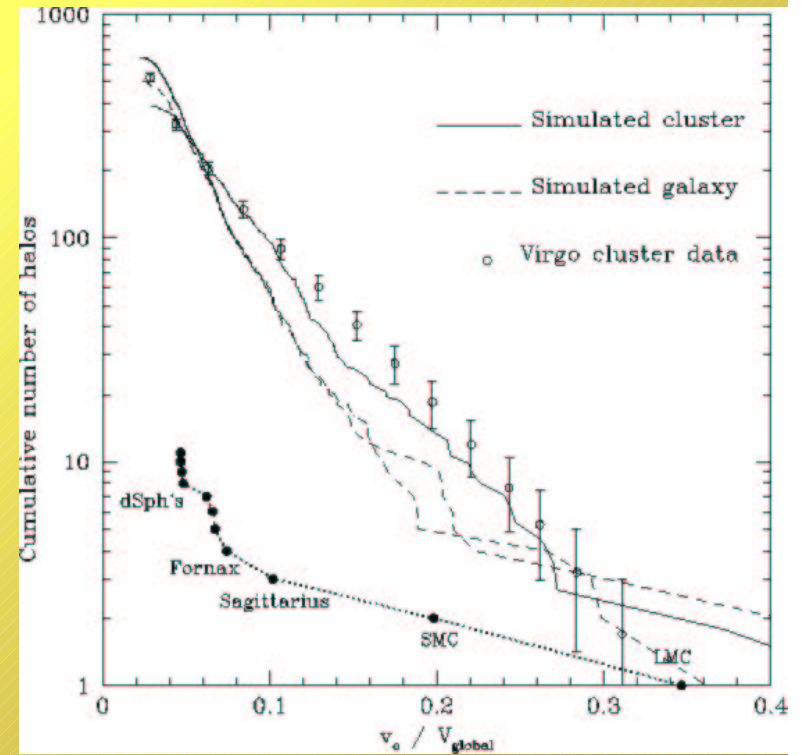
N-body simulations show more than 10 times as many dwarf galaxies in typical galactic halo than are observed in Milky Way (Moore et al. 1999; Klypin et al. 1999)



Cluster

galactic
halo

→ 300 kpc



The self-interacting dark matter solution (Spergel & Steinhardt 1999):

Hypothesize that dark matter can elastically scatter from itself

Small self-interaction leads to energy transport that reduces sharp subgalactic features like cusp and substructure.

Required cross section is $10^{-(21-24)} \text{ cm}^2 (M_x/\text{GeV})$,
or self-opacity $0.5 \times (1-10) \text{ cm}^2/\text{g}$ (Spergel
& Steinhardt 2000; Dave et al. 2000).

Weaker interaction doesn't work; larger
interaction leads to halo core collapse on
Hubble time (e.g., Moore et al. 2000, 2002; Yoshida
et al. 2002; Burkert 2000; Kochanek & White 2000)

“Particle physics” reaction:

- This is a BIG opacity, bigger than opacity for photon through plasma.
- Required elastic–scattering cross section at least 13 orders of magnitude than allowed for WIMP; problem even worse with axions.
- More generally, for point particles, required cross section violates unitarity for $M_x < 12 \text{ GeV}$

(MK & Griest 1990; Hui 2002)

- SIDM must be extended object . But what is it (e.g. Q–balls, Wimpzillas)? How does it get produced? Why does it have density comparable to critical density?

What about the motivation? Are there are other solutions to cusp/substructure problems?

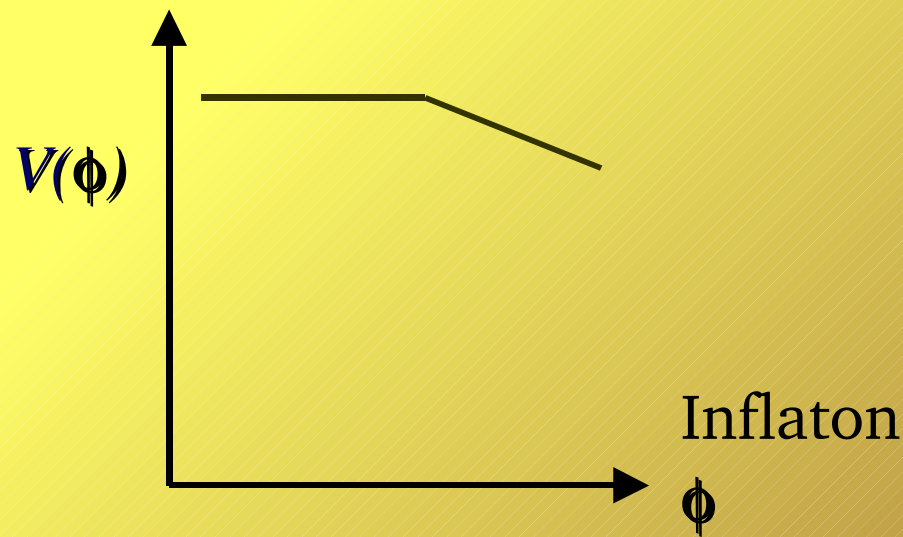
Astrophysical solutions to dwarf–galaxy dearth:

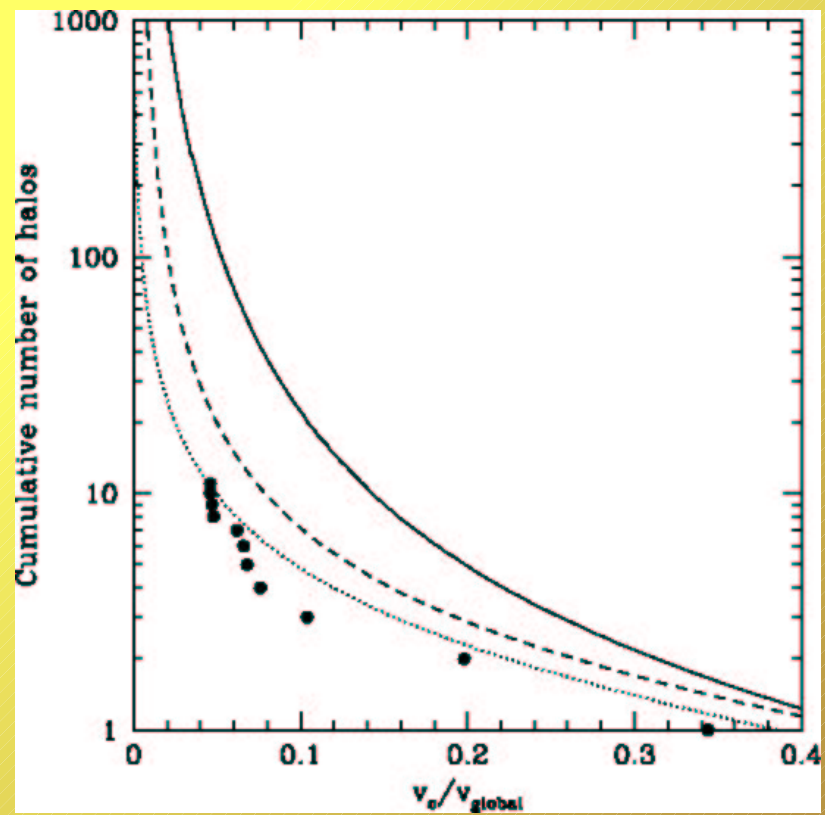
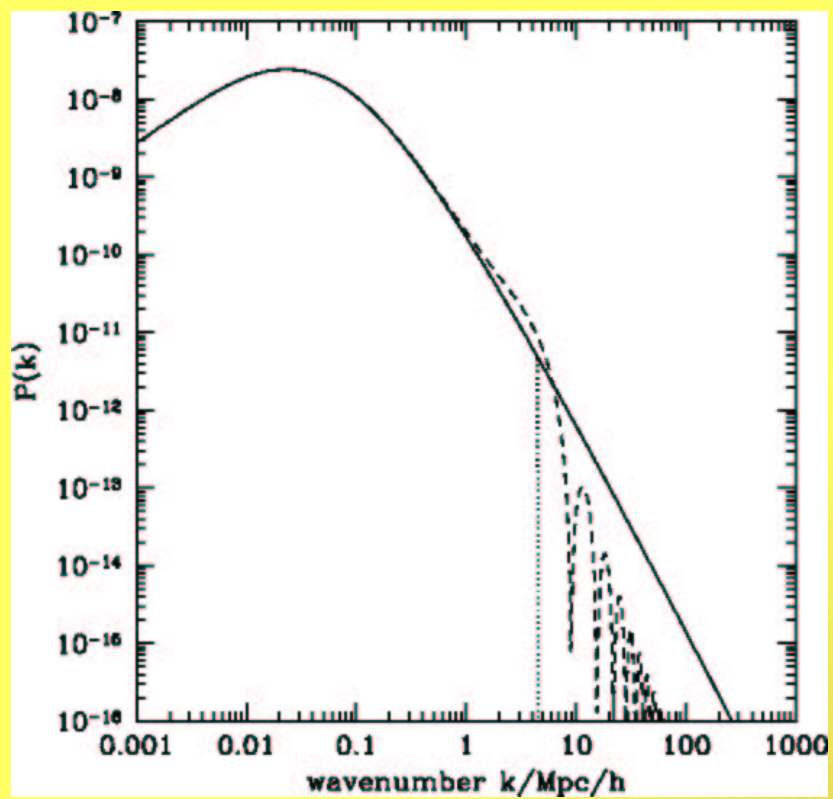
- Gas in small halos could be ejected by supernovae;
- Dwarf–galaxy formation could be suppressed by reionization (e.g., Benson et al. 2002; Bullock, Kravtsov, Weinberg 2000)
- May just be discrepancy between sub–halo velocity dispersion and dispersion of observed stellar component of dwarf galaxies (Stoehr et al. 2002)

Another possible resolution:
Power suppression on small scales from
inflation with broken scale invariance

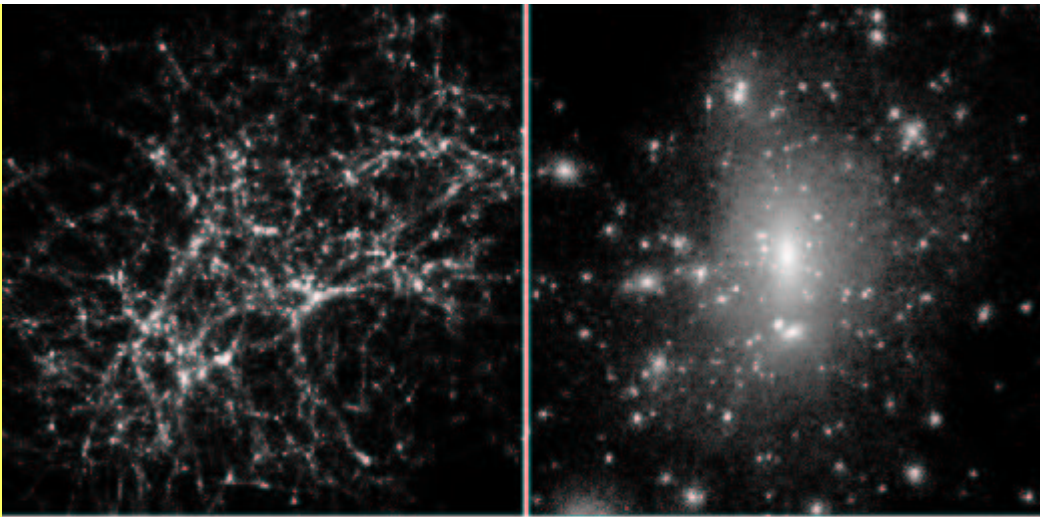
MK&Liddle, PRL 84, 4525 (2000)

I Yokoyama, PRD, 2000

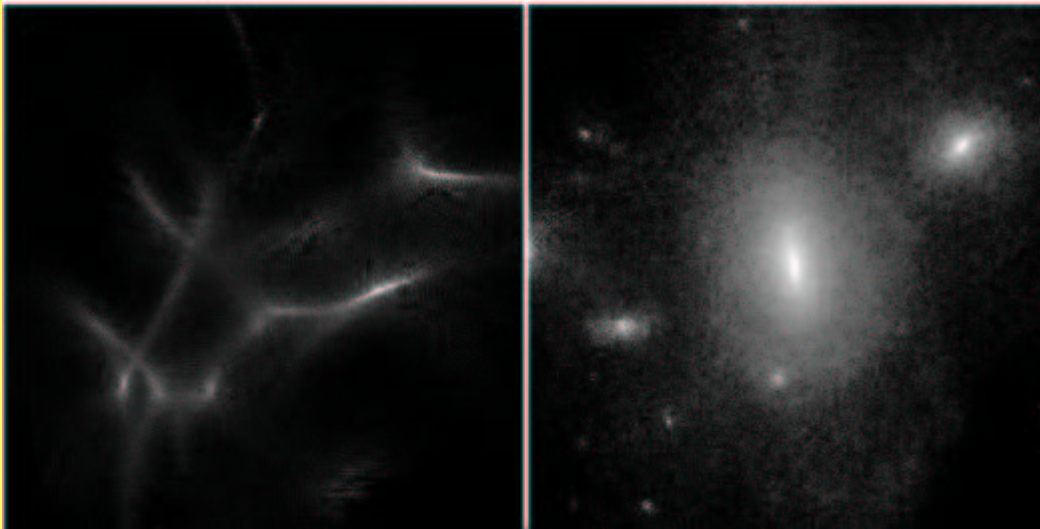




----- ad hoc
 - - - BSI



Standard
CDM



Power
suppressed
on small scales

Turnaround

Today

Moore et al, astro-ph/9903164

What about cusps?

Baryon–DM interaction may remove cusps; e.g., rapidly rotating bar produces time–varying gravitational potential that may kick DM out of cusp (e.g., Binney, Dehnen, Silk; Katz, Weinberg; Sellwood, Milosavljevic)

Astrophysical Tests of SIDM:

Need to account for existence of DM cores in DM-dominated dwarf galaxies; typical core radii $r \sim 2$ kpc and velocity dispersions $v \sim 50$ km/sec.

Proposed velocity dependences for scattering cross section are either constant in velocity or $1/v$.

If constant-velocity, then core radii should scale as $r \propto v^{3/2}$. So, for cluster with $v \sim 1000$ km/sec, core radius should be > 100 kpc.

Miralda–Escude 2000: Misalignment of lens arcs in cluster MS2137–23 suggests elliptical (as opposed to spherical expected for SIDM) core <70 kpc. Constrains cross section <0.02 cm²/g.

Similar arguments (based on size as well as shape of cluster cores, as well as lensing statistics) from **Yoshida et al. 2000, Meneghetti et al. 2001, Dahle et al. 2002.** find <0.1 cm²/g.

However, is consistent if cross section $\propto 1/v^k$.

However, if cross section $\propto 1/v^k$, then $r \propto v^{(3-k)/2}$
and $\rho \propto v^{(k-1)/2}$ (Miralda-Escude).

X-ray observations of giant elliptical NGC 4636
find very dense dark halo with profile $r^{-1.2}$,
with very stringent constraints to core.
Eliminates $1/v$ cross section
(Loewenstein & Mushotzky 2002)

Comments/Conclusions

- SIDM is interesting idea; provides new theoretical challenges and opportunities for new tests of dark–matter properties.
- But, physics of galaxy formation is nasty; ionization state and metallicity of gas, star formation, supernova feedback, merger history, bar formation, baryon/DM dynamical friction, are all poorly understood, but will be required for quantitative comparison of data and theory. Thus, discrepancies between theory and observations do not "demand" new DM properties.
- SIDM requires DM particles that arise only at higher order in speculation theory.
- Evidence for cusps in ellipticals and clusters now provides very stringent constraints (rules out?) SIDM